

Combinatorial Evolution and Forecasting of Communication Protocol ZigBee

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Abstract—The article addresses combinatorial evolution and forecasting of communication protocol for wireless sensor networks (ZigBee). Morphological tree structure (a version of and-or tree) is used as a hierarchical model for the protocol. Three generations of ZigBee protocol are examined. A set of protocol change operations is generated and described. The change operations are used as items for forecasting based on combinatorial problems (e.g., clustering, knapsack problem, multiple choice knapsack problem). Two kinds of preliminary forecasts for the examined communication protocol are considered: (i) direct expert based forecast, (ii) two computed forecasts (usage of multicriteria decision making and combinatorial optimization problems): $\hat{\Phi}$ and $\bar{\Phi}$. Further, the obtained three preliminary forecasts above are aggregated to build resultant forecasts: Θ^I (aggregation strategy I) and Θ^{II} (aggregation strategy II).

Index Terms—Communication protocol, wireless sensor network, systems evolution, forecast, combinatorial optimization, multicriteria decision making, aggregation

I. INTRODUCTION

The significance of systems evolution/development and forecasting is increasing (e.g., [2], [5], [14]). In the case of hierarchical modular systems, combinatorial approaches to systems evolution and forecasting were proposed in ([8], [9], [11]). The approaches are based on hierarchical system modeling and usage of multicriteria decision making and combinatorial optimization problems. Some applied examples of combinatorial evolution and forecasting (e.g., electronic equipment, standard for transmission of multimedia data) have been described in ([9], [11], [12]). In recent years, wireless sensor networks are widely used in many domains (e.g., [1], [3], [4], [5], [6], [7], [16], [17]). Here many research works are targeted to analysis and synthesis (e.g., optimization) of communication protocols for wireless sensor networks (e.g., [3], [7], [15]). In the paper, combinatorial evolution and forecasting of protocol ZigBee for wireless sensor networks ([3], [7], [16]) are considered. A morphological tree structure (a version of *and-or tree*) is used as a hierarchical modular model for the protocol. Three generations of ZigBee protocol are examined: (1) ZigBee 2004 S_1 , (2) ZigBee 2006 S_2 , and (3) ZigBee PRO S_3 . A set of protocol change operations (between protocol generations above) is generated and described. The change operations are used as items for forecasting based on combinatorial problems (e.g., clustering, knapsack problem,

multiple choice knapsack problem, multicriteria ranking). Two kinds of preliminary forecasts for the examined communication protocol are considered: (i) direct expert based forecast \hat{S}_4 ($\hat{\Phi}$), (ii) two computed forecasts (usage of multicriteria decision making and combinatorial optimization problems): $\hat{\Phi}$ and $\bar{\Phi}$. Further, the obtained three preliminary forecasts above are aggregated to build resultant forecasts: Θ^I (aggregation strategy I) and Θ^{II} (aggregation strategy II).

A flowchart of the article is as follows: (1) designing a general tree-like model of ZigBee protocol; (2) description of three protocol generations (including their structures and components); (3) expert judgement to obtain a direct expert based (preliminary) forecast; (4) extraction of changes between neighbor protocol generations; (5) generation of an integrated set of basic change operations; (6) evaluation of change operations upon criteria; (7) solving of combinatorial problems (ranking, clustering) and forecasting (e.g., multicriteria choice knapsack problem) to obtain computed preliminary forecasts; and (8) aggregation of the obtained preliminary forecasts to build a resultant aggregated forecast(s) (two aggregation strategies are used). The paper is based on preliminary materials: (i) conference paper (combinatorial evolution, preliminary forecasts [13]) and (ii) electronic preprint (aggregation approaches and aggregation example [11]).

II. GENERAL SCHEME

A general framework of combinatorial evolution and forecasting for modular systems in case of three system generations is depicted in Fig. 1 ([9], [10]).

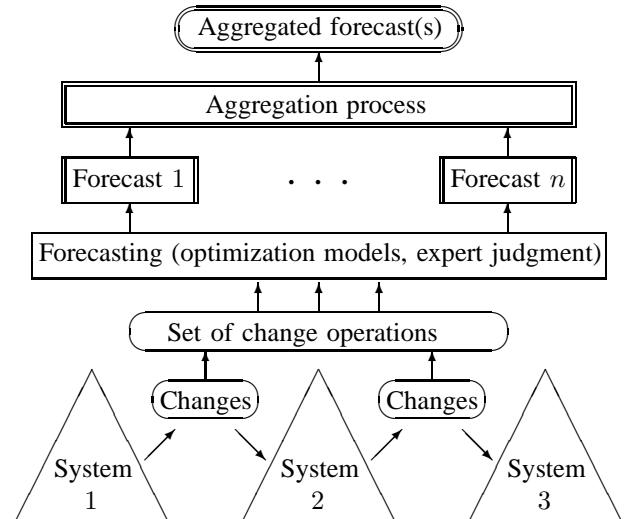


Fig. 1. General framework ([9], [10])

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Here a hierarchical multi-layer system model “morphological tree” is used ([9], [11]): (i) tree-like system model, (ii) set of leaf nodes as basic system parts/components, (iii) sets of design alternatives (DAs) for each leaf node, (iv) DAs rankings (i.e., ordinal priorities), and (v) compatibility estimates between DAs for different leaf nodes. This “morphological tree” model is a version of “and-or tree”. In this paper, a simplified version of our “morphological tree” is used without estimates of DAs and their compatibility. Our scheme for evolution and forecasting of ZigBee protocol is depicted in Fig. 2.

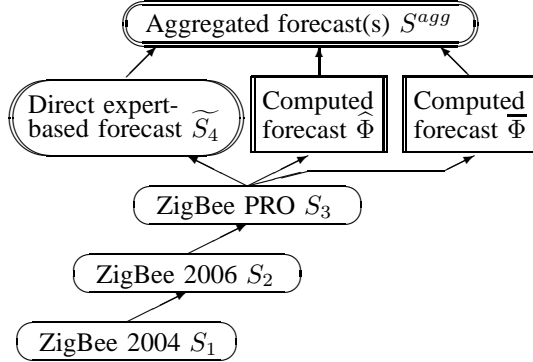


Fig. 2. Evolution, forecasting for ZigBee protocol

III. DESCRIPTION OF PROTOCOL GENERATIONS

Let us consider hierarchical structures (as *and/or trees*) for three basic versions of ZigBee protocols. The structure of generation 1 ZigBee 2004 (S_1) is the following:

1. Interference avoidance A : A_1 (PAN coordinator selects best available RF channel/Network ID at startup time).
2. Automated/distributed address management B : B_1 (Device addresses automatically assigned using a hierarchical, distributed scheme).
3. Centralized data collection C : 3.1. Low-overhead data collection by ZigBee Coordinator G : G_1 (Fully supported), 3.2. Low-overhead data collection by other devices H : H_1 (Under special circumstances).
4. Network scalability D : D_1 (Network scales up to the limits of the addressing algorithm. Typically, networks with tens to hundreds of devices are supported).
5. Message size E : E_1 (<100 bytes. Exact size depends on services employed, such as security).
6. Robust mesh networking F : F_1 (Fault tolerant routing algorithms respond to changes in the network and in the RF environment).

The structure of generation 2 ZigBee 2006 (S_2) is the following:

1. Interference avoidance A : A_1 (PAN coordinator selects best available RF channel/Network ID at startup time).
2. Automated/distributed address management B : B_1 (Device addresses automatically assigned using a hierarchical, distributed scheme).
3. Group addressing I : I_1 (Devices can be assigned to groups, and whole groups can be addressed with a single frame).
4. Centralized data collection C : 4.1. Low-overhead data collection by ZigBee Coordinator G : G_1 (Fully supported),

4.2. Low-overhead data collection by other devices H : H_1 (Under special circumstances).

5. Network scalability D : D_1 (Network scales up to the limits of the addressing algorithm. Typically, networks with tens to hundreds of devices are supported).

6. Message size E : E_1 (<100 bytes. Exact size depends on services employed, such as security).

7. Standardized commissioning K : K_1 (Standardized startup procedure and attributes support the use of commissioning tools in a multi-vendor environment).

8. Robust mesh networking F : F_1 (Fault tolerant routing algorithms respond to changes in the network and in the RF environment).

9. Cluster Library support L : L_1 (The ZigBee Cluster Library, as an adjunct to the stack, standardizes application behavior across profiles and provides an invaluable resource for profile developers).

The structure of generation 3 ZigBee PRO (S_3) is the following:

1. Interference avoidance A' : 1.1. Startup Procedure of Channel Acquisition M : M_1 (PAN coordinator selects best available RF channel/Network ID at startup time), 1.2. Channel Hopping N : N_1 (Ongoing interference detection and adoption of a new operating RF channel and/or Network ID).

2. Automated/distributed address management B : B_2 (Device addresses automatically assigned using a stochastic scheme.)

3. Group addressing I : I_1 (Devices can be assigned to groups, and whole groups can be addressed with a single frame).

4. Centralized data collection C' : 4.1. Low-overhead data collection by ZigBee Coordinator G : G_1 (Fully supported), 4.2 Low-overhead data collection by other devices H : H_1 (Under special circumstances), 4.3. Many-to-one routing Q : Q_1 (Whole network discovers the aggregator in one pass), and 4.4. Source routing P : P_1 (Aggregator responds to all senders in an economical manner).

5. Network scalability D : D_2 (An addressing algorithm that relaxes the limits on network size. Networks with hundreds to thousands of devices are supported).

6. Message size E : E_2 (Large messages, up to the buffer capacity of the sending and receiving devices, are supported using Fragmentation and Reassembly).

7. Standardized commissioning K : K_1 (Standardized startup procedure and attributes support the use of commissioning tools in a multi-vendor environment).

8. Robust mesh networking F' : 8.1. Fault tolerant routing algorithms R : R_1 (Response to changes in the network and in the RF environment), 8.2. Neighborhood tables T : T_1 (Kept by every device).

9. Cluster library support L : L_1 (Standardizes application behavior across profiles).

Here two equivalent descriptions of communication protocol are considered: (a) a structure as a set of protocol components, (b) a basic protocol and a set of change (improvement) operations. In this paper, protocol S_3 is considered as a basic protocol for forecasting.

Further, let us consider a direct expert-based forecast (version of generation 4) ZigBee/IP(6LoWPAN) 2010 (\tilde{S}_4) as the following:

1. Interference avoidance A' : 1.1. Startup Procedure of Channel Acquisition M : M_1 (PAN coordinator selects best available RF channel/Network ID at startup time), 1.2. Channel Hopping N : N_1 (Ongoing interference detection and adoption of a new operating RF channel and/or Network ID).

2. Automated/distributed address management B : B_1 (Device addresses automatically assigned using a hierarchical, distributed scheme), B_2 (Device addresses automatically assigned using a stochastic scheme).

3. Group addressing I : I_1 (Devices can be assigned to groups, and whole groups can be addressed with a single frame).

4. Centralized data collection C'' : 4.1. Low-overhead data collection by 6LoWPAN Coordinator G : G_1 (Fully supported), 4.2 Low-overhead data collection by other devices H : H_1 (Under special circumstances), 4.3. Many-to-one routing Q : Q_1 (Whole network discovers the aggregator in one pass), and 4.4. 6LoWPAN multicast/broadcast support V : V_1 (flooding), V_2 (unicasting to a PAN coordinator).

5. Network scalability D : D_2 (An addressing algorithm that relaxes the limits on network size. Networks with hundreds to thousands of devices are supported).

6. Message size E : E_3 (Large messages, up to the buffer capacity of the sending and receiving devices using 6LoWPAN Fragmentation and Reassembly).

7. Standardized commissioning K : K_1 (Standardized startup procedure and attributes support the use of commissioning tools in a multi-vendor environment).

8. Robust mesh networking F'' : 8.1. 6LoWPAN Approaches U : U_1 (Route-over), U_2 (Mesh-under).

9. Cluster Library support L : L_1 (Standardizes application behavior across profiles).

10. Web services support W : W_1 (condensed HTTP with tokenized XML data).

Fig. 3, 4, 5, and 6 illustrate the described protocol structures.

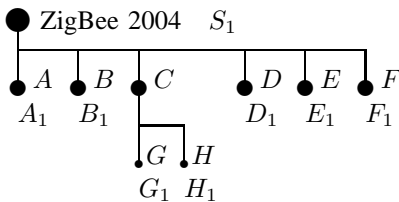


Fig. 3. Structure of generation 1

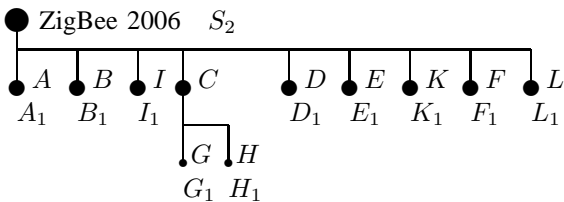


Fig. 4. Structure of generation 2

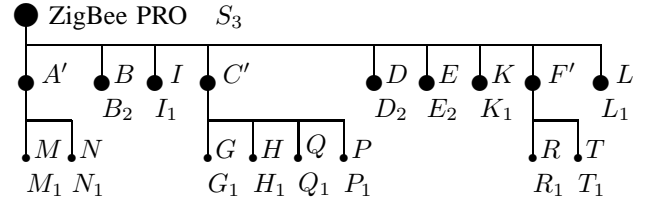


Fig. 5. Structure of generation 3

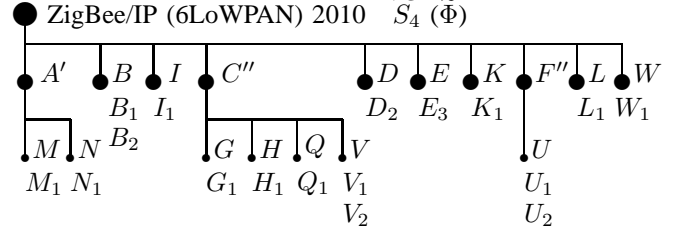


Fig. 6. Structure of direct expert-based forecast

IV. CHANGE OPERATIONS

Table 1 integrates changes in protocol generations.

Table 1. Changes in protocol generations

Kind of change	Change	Operation type
$S_1 \Rightarrow S_2$		
2.Subsystem addition	(a) I, I_1	O_7
	(b) K, K_1	O_7
	(c) L, L_1	O_7
$S_2 \Rightarrow S_3$		
1.Element change	(a) $B_1 \rightarrow B_2$	O_1
	(b) $D_1 \rightarrow D_2$	O_1
	(c) $E_1 \rightarrow E_2$	O_1
2.Subsystem extension	(a) $C \rightarrow C'$: (i) Q, Q_1	O_5
	(i) P, P_1	O_5
	(b) $A \rightarrow A'$: (i) M, M_1	O_5
	(ii) N, N_1	O_5
	(c) $F \rightarrow F'$: (i) R, R_1	O_5
	(ii) T, T_1	O_5
$S_3 \Rightarrow \tilde{S}_4$		
1.Element addition	B_1	O_3
2.Element change	$E_2 \rightarrow E_3$	O_1
3.Subsystem addition	W, W_1	O_7
4.Subsystem change	(a) $C' \Rightarrow C''$: $P \rightarrow V, V_1, V_2$	O_5
	(b) $F' \Rightarrow F''$: U, U_1, U_2	O_5

Now it is necessary to generate a basic set of possible change/improvement operations. This process is based on the following: (a) obtained protocol changes (Table 1), (b) additional expert judgement. Thus, the resultant set of the possible operations is;

1. Φ_1 : I_1 . Introduction of groups allows to transmit a single frame to all devices assigned to a group. It has its positive impact on scalability and reliability of the network. The cost and the implementation time are negatively related

to device association list introduction. The maintenance time will remain the same because of the group maintenance tasks time reduction compensation by an additional time required for handling the device association lists.

2. Φ_2 : K_1 . Standardized commissioning decreases maintenance efforts and cost; increases scalability and reliability.

3. Φ_3 : L_1 . ZigBee Cluster Library standardizes application behavior resulting in better reliability and lower maintenance efforts.

4. Φ_4 : $B_1 \rightarrow B_2$. Stochastic device address management does not require the knowledge of network hierarchy resulting in improved reliability and mobility. While increasing the risk of collision it allows to assign more addresses.

5. Φ_5 : $D_1 \rightarrow D_2$. Addressing algorithm limits relaxation drastically increases scalability.

6. Φ_6 : $E_1 \rightarrow E_2$. Message size enlargement will reduce the time necessary for WSN application development and maintenance while improving the reliability.

7. Φ_7 : Q_1 . Many-to-one routing reduces application implementation time but can cause aggregator buffer overflow.

8. Φ_8 : P_1 . Source routing also reduces application implementation time but improving the reliability. Source routing allows easier troubleshooting, improved trace-route, and enables a node to discover all the possible routes to a host. It also allows a source to directly manage network performance by forcing packets to travel over one path to prevent congestion on another.

9. Φ_9 : M_1 . Startup channel acquisition procedure is an interference avoidance mechanism requiring an additional resources but improving reliability, mobility, scalability and optimizing maintenance efforts.

10. Φ_{10} : N_1 . Channel hopping requires more resources but brings an additional mobility, reliability while reducing maintenance efforts.

11. Φ_{11} : R_1 . Fault tolerant routing algorithms aims at reliability and mobility.

12. Φ_{12} : T_1 . Neighborhood tables need memory but positively influence on scalability, reliability and mobility.

13. Φ_{13} : B_1 . The combination of both address distribution schemes increase mobility of nodes while keeping maintenance costs at acceptable level.

14. Φ_{14} : $E_2 \rightarrow E_3$. Providing large message sizes by 6LoWPAN fragmentation and reassembly mechanisms significantly improves scalability through heterogeneous WSNs.

15. Φ_{15} : W_1 . Porting HTTP to WSN level is a significant step towards ubiquitous user-friendly data propagation.

16. Φ_{16} : $P \rightarrow V, V_1, V_2$. 6LoWPAN multicast/broadcast support will reduce the development time needed in heterogeneous WSNs, increase overall system reliability and usability.

17. Φ_{17} : U_1, U_2 . 6LoWPAN mesh networking approaches are necessary to provide an interoperable platform for heterogeneous WSNs that would lead to better scalability.

Here the following attributes (criteria) for an assessment of the operations are used: (1) cost Υ_1 ; (2) required time for implementation Υ_2 ; (3) performance Υ_3 ; (4) decreasing a cost of maintenance Υ_4 ; (5) scalability Υ_5 ; (6) reliability Υ_6 ; (7) mobility Υ_7 ; and (8) usability value Υ_8 . An ordinal scale [1,5] is used for each criterion: 1 corresponds to “strong negative

effect”, 2 corresponds to “negative effect”, 3 corresponds to “no changes”, 4 corresponds to “positive effect”, and 5 corresponds to “strong positive effect”.

Table 2 contains improvement operations $\Phi_1, \dots, \Phi_i, \dots, \Phi_{17}$ and their estimates upon criteria.

Table 2. Estimates on criteria, priorities

Improvement operation	Υ_1	Υ_2	Υ_3	Υ_4	Υ_5	Υ_6	Υ_7	Υ_8	Priorities r_i
Φ_1	3	3	3	3	4	4	3	4	1
Φ_2	4	2	3	4	4	4	3	4	2
Φ_3	3	4	3	4	3	5	3	4	1
Φ_4	4	4	2	3	4	4	5	3	2
Φ_5	3	3	3	3	5	3	3	4	1
Φ_6	3	4	3	4	3	4	3	3	3
Φ_7	3	4	3	3	3	2	3	3	4
Φ_8	3	4	4	4	3	4	3	3	2
Φ_9	2	3	4	4	4	4	4	3	1
Φ_{10}	2	3	4	4	3	4	4	3	1
Φ_{11}	3	3	3	3	3	4	4	3	3
Φ_{12}	2	3	4	3	4	4	4	3	1
Φ_{13}	3	3	3	4	3	3	4	3	3
Φ_{14}	3	3	3	3	5	3	3	3	2
Φ_{15}	3	3	2	3	4	3	3	5	2
Φ_{16}	3	4	3	3	3	4	3	4	3
Φ_{17}	3	3	4	3	4	3	3	3	3

In addition, it is reasonable to consider some types of binary relations over the improvement operations (e.g., *equivalence*, *complementarity*, *precedence*).

V. COMPUTATION OF FORECASTS

Results of multicriteria ranking for operations $\{\Phi_1, \dots, \Phi_{17}\}$ are presented in Table 2 (Fig. 7) (an outranking technique was used; 1 corresponds to the best level). Priorities of operations can be used as a “profit” (here: $c_i = 4 - r_i$).

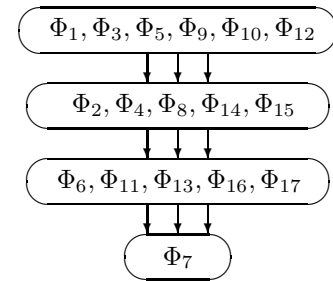


Fig. 7. Results of multicriteria ranking

Further, let us consider the usage of knapsack problem:

$$\max \sum_{i=1}^{17} c_i x_i \quad s.t. \quad \sum_{i=1}^{17} a_i x_i \leq b, \quad x_i \in \{0, 1\}, \quad i = \overline{1, 17}.$$

For an assessment of resource requirements (i.e., a_i) the following estimates (additional expert judgment) are used: $\{2, 3, 4, 1, 1, 2, 2, 3, 2, 4, 3, 3, 3, 3, 2, 4\}$. In this case, independence of improvement operations is assumed. Thus, the following solution (forecast) is obtained (total cost constraint

$b = 16$): $\hat{\Phi} = \{\Phi_1, \Phi_2, \Phi_4, \Phi_5, \Phi_6, \Phi_7, \Phi_8, \Phi_9\}$ (a simple greedy algorithm was used).

Results of clustering for operations $\{\Phi_1, \dots, \Phi_{17}\}$ (9 steps of an agglomerative algorithm) are the following: (i) cluster 1: $\Omega^1 = \{\Phi_1, \Phi_3, \Phi_6, \Phi_8, \Phi_{16}\}$, (ii) cluster 2: $\Omega^2 = \{\Phi_2\}$, (iii) cluster 3: $\Omega^3 = \{\Phi_4\}$, (iv) cluster 4: $\Omega^4 = \{\Phi_5, \Phi_{14}, \Phi_{17}\}$, (v) cluster 5: $\Omega^5 = \{\Phi_7\}$, (vi) cluster 6: $\Omega^6 = \{\Phi_9, \Phi_{10}, \Phi_{12}\}$, (vii) cluster 7: $\Omega^7 = \{\Phi_{11}, \Phi_{13}\}$, and (viii) cluster 8: $\Omega^8 = \{\Phi_{15}\}$. Now it is possible to examine multiple choice knapsack problem. It is assumed that operations which belong to the same cluster are very close (about equivalent) and the only one operation from each cluster is selected (if it is possible by resource constraint). The problem formulation is:

$$\max \sum_{i=1}^8 \sum_{j=1}^{q_i} c_{ij} x_{ij}, \quad s.t. \quad \sum_{i=1}^8 \sum_{j=1}^{q_i} a_{ij} x_{ij} \leq b,$$

$$\sum_{j=1}^{q_i} x_{ij} = 1 \quad i = \overline{1, 8}, \quad x_{ij} \in \{0, 1\}.$$

Priorities and resource requirements are examined as in knapsack problem. A resultant solution (forecast) is the following (total cost constraint $b = 17$): $\bar{\Phi} = \{\Phi_2, \Phi_4, \Phi_5, \Phi_6, \Phi_7, \Phi_9, \Phi_{11}, \Phi_{15}\}$ (a simple greedy algorithm was used).

Fig. 8 and Fig. 9 depict structures which illustrate solutions (i.e., corresponding groups of operations) for $\hat{\Phi}^2$ and $\bar{\Phi}^2$.

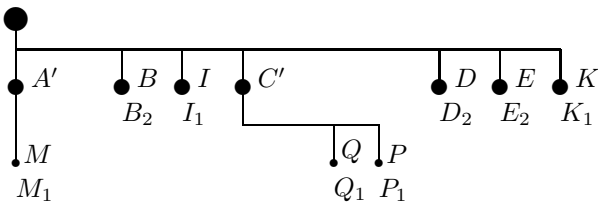


Fig. 8. Forecast $\hat{\Phi}$ (knapsack problem)

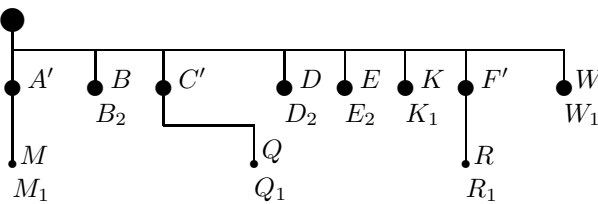


Fig. 9. Forecast $\bar{\Phi}$ (multiple choice problem)

Three obtained solutions (forecasts) can be analyzed:

(1) direct expert based forecast \tilde{S}_4 (Fig. 6), i.e., corresponding group of improvement operations: $\tilde{\Phi} = \{\Phi_1, \Phi_2, \Phi_3, \Phi_5, \Phi_7, \Phi_9, \Phi_{10}, \Phi_{13}, \Phi_{14}, \Phi_{15}, \Phi_{16}, \Phi_{17}\}$;

(2) two computation-based forecasts: $\hat{\Phi}$ (Fig. 8) and $\bar{\Phi}$ (Fig. 9).

Here the following integrated estimates of the solutions are examined (a simplified case): (i) total “profit”: $\sum_{\forall \Phi_i \in \tilde{\Phi}} c_i$, $\sum_{\forall \Phi_i \in \hat{\Phi}} c_i$, $\sum_{\forall \Phi_i \in \bar{\Phi}} c_i$; (ii) total required resource: $\sum_{\forall \Phi_i \in \tilde{\Phi}} a_i$, $\sum_{\forall \Phi_i \in \hat{\Phi}} a_i$, $\sum_{\forall \Phi_i \in \bar{\Phi}} a_i$. The solutions belong to a layer of Pareto-efficient solutions (Fig. 10).

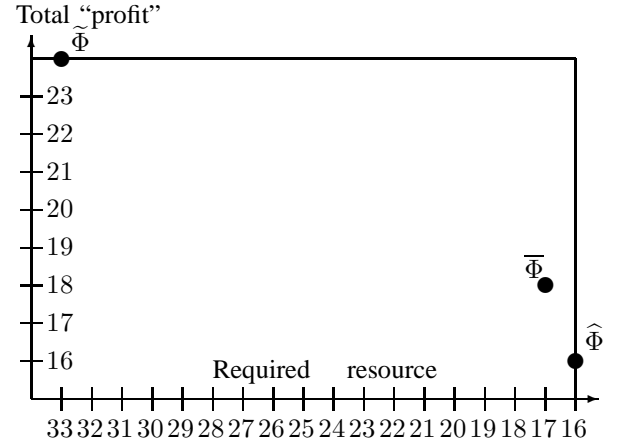


Fig. 10. Comparison of three forecasts

VI. AGGREGATION OF PRELIMINARY FORECASTS

Two aggregation strategies for aggregation of three preliminary forecasts ($\tilde{\Phi}$, $\hat{\Phi}$, $\bar{\Phi}$) are considered [11]: (i) extension (addition) strategy I (i.e., a “kernel” of a substructure of the initial solutions is extended by addition of some additional elements), (ii) compression (deletion) strategy II (i.e., a superstructure of the initial solutions is compressed by deletion of some its elements). Fig. 11 illustrates the substructure and superstructure (as sets of change operations):

(i) substructure: $\tilde{\Phi} \cap \hat{\Phi} \cap \bar{\Phi} = \{\Phi_2, \Phi_5, \Phi_6\}$.

(ii) superstructure: $\tilde{\Phi} \cup \hat{\Phi} \cup \bar{\Phi} = \{\Phi_1, \Phi_2, \Phi_3, \Phi_4, \Phi_5, \Phi_6, \Phi_7, \Phi_8, \Phi_9, \Phi_{10}, \Phi_{11}, \Phi_{13}, \Phi_{14}, \Phi_{15}, \Phi_{16}, \Phi_{17}\}$.

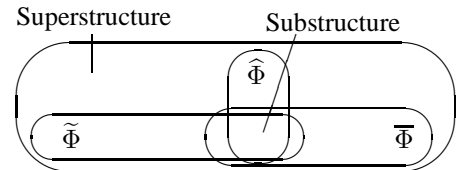


Fig. 11. Substructure and superstructure

A list of addition operations (for strategy I) is presented in Table 3 (operations and their estimates correspond to Table 2).

Table 3. Addition operations (estimates, priorities)

i	Improvement operation	Variable	Υ_1	Υ_2	Υ_3	Υ_4	Υ_5	Υ_6	Υ_7	Υ_8	Priorities r_i
1	$J_1(\Phi_{10})$	x_1	2	3	4	4	3	4	4	3	1
2	$B_1(\Phi_{13})$	x_2	3	3	3	4	3	3	4	3	3
3	$U_1 \& U_2$ (Φ_{17})	x_3	3	3	4	3	4	3	3	3	3
4	$L_1(\Phi_3)$	x_4	3	4	3	4	3	5	3	4	1
5	$W_1(\Phi_{15})$	x_5	3	3	2	3	4	3	3	5	2

The addition problem (simplified knapsack problem) is:

$$\max \sum_{i=1}^5 c_i x_i \quad s.t. \quad \sum_{i=1}^5 a_i x_i \leq b, \quad x_i \in \{0, 1\}.$$

Cost estimates (by criterion Υ_1) are used as $\{a_i\}$, priorities $\{r_i\}$ are used as (transform to) $\{c_i\}$, and $b = 8.00$. A resultant solution for strategy I is depicted in Fig. 12 ($x_1 = 1$, $x_2 = 1$,

$x_3 = 0, x_4 = 0, x_5 = 1$) (a simple greedy algorithm was used).

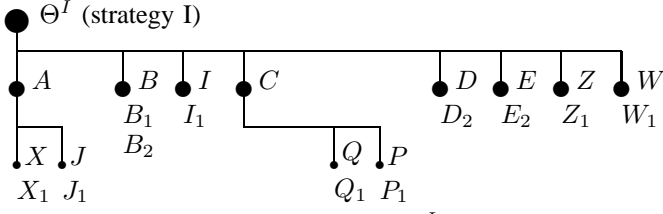


Fig. 12. Aggregated forecast Θ^I (strategy I)

A list of deletion operations (for strategy II) is presented in Table 4.

Table 4. Deletion operations (estimates, priorities)

i	Deletion operation	Variable	Υ_1	Υ_2	Υ_3	Υ_4	Υ_5	Υ_6	Υ_7	Υ_8	Priorities r_i
1	$J_1(\Phi_{10})$	x_1	2	3	4	4	3	4	4	3	1
2	$B_1(\Phi_{13})$	x_2	3	3	3	4	3	3	4	3	3
3	$Q_1(\Phi_7)$	x_3	3	4	3	3	3	2	3	3	4
4	$P_1(\Phi_8)$	x_4	3	4	4	4	3	4	3	3	2
5	$E_3(\Phi_{14})$	x_5	3	3	3	3	5	3	3	3	2
6	$L_1(\Phi_3)$	x_6	3	4	3	4	3	5	3	4	1
7	$U_1 \& U_2$ (Φ_{17})	x_7	3	3	4	3	4	3	3	3	3

The deletion problem (knapsack problem with minimization of the objective function) is:

$$\min \sum_{i=1}^7 c_i x_i \quad s.t. \sum_{i=1}^7 a_i x_i \geq b, \quad x_i \in \{0, 1\}.$$

Cost estimates are (by criterion Υ_1) used as $\{a_i\}$, priorities $\{r_i\}$ are used as (transform to) $\{c_i\}$, and $b = 8.00$. A resultant solution based on strategy II is depicted in Fig. 13 ($x_1 = 0, x_2 = 1, x_3 = 1, x_4 = 1, x_5 = 0, x_6 = 0, x_7 = 1$) (a simple greedy algorithm was used).

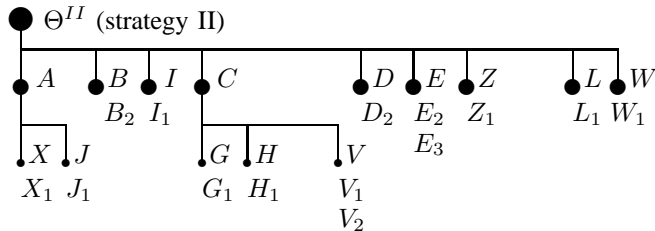


Fig. 13. Aggregated forecast Θ^{II} (strategy II)

VII. CONCLUSION

In the paper, we have firstly suggested and described the following: (a) a hierarchical modular model for communication protocol ZigBee, (b) typical change operations (between protocol generations) and their evaluation, (c) a direct expert-based protocol ZigBee/IP (6LoWPAN) 2010, (d) two computed protocol forecasts, (e) aggregation of the obtained protocol forecasts to build two aggregated forecasts.

It is reasonable to consider the following future research directions: 1. consideration and usage of special comparison

analysis approaches for protocol forecasts; 2. examination of other communication protocols (and other applied modular systems); 3. usage of fuzzy set based approaches and corresponding problems/models; 4. usage of AI-based methods. and 5. usage of the approaches to combinatorial evolution and forecasting in engineering education.

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